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Achievable Aperture Improvements for the Recycler

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Abstract

Following more than two years of operation, we can confidently assert that the Recycler operation as a high intensity stacking ring using slip stacking is seriously impacted by limited aperture. We will propose modest changes in the aperture using only a few new dipoles and re-using existing quadrupoles to remove important aperture restrictions where loss control is now difficult. We hope to evaluate this option as we continue with other improvements.

1 Introduction

Studies in the Recycler have identified areas of losses that are likely to remain a concern after the commissioning of the Recycler collimation system that will localize substantial halo losses. We are especially hopeful that either the initial Phase I implementation of the collimators, or two further collimators in Phase II, will reduce the activation rate for regions near the Lambertson transfer magnets at 102, 232, 402 and 522. Even so, reductions in losses due to these aperture restrictions may be an ongoing issue. Additionally, losses in regular cells between defocusing gradient magnets may remain a concern. Specifically, this note addresses the horizontal aperture adjacent to the Lambertson magnets and the vertical aperture in the arcs, exploring a similar approach in the two areas. We propose that we replace a gradient magnet with a quadrupole and a dipole. Other alternatives are suggested in the conclusion.

This note suggests building blocks for a modified lattice which provides improved apertures in localized portions of the Recycler. We expect that one can substitute a quadrupole and a dipole for existing gradient magnets while matching the lattice properties either exactly or nearly so. This approach will need to be examined with real lattice calculations as an initial part of any effort to develop this idea. The requirement would be to match the bending and focusing properties locally or perhaps to demonstrate that the imperfect match leaves the Recycler lattice with no serious impairment or, given existing imperfections, even make some improvement. One must consider β and α but also dispersion, bend center, and angles while enhancing the available beam pipe aperture.

2 An Improved Recycler Vertical Aperture in the Regular Cells

In the regular cells of the arcs, the vertical beam size is so near to the design beam tube height at the high β_y points that we long for additional aperture. At these locations the bending and focusing is provided by RGD (horizontally defocusing) gradient dipoles. The high β_y occurs in beam pipe between two RGD magnets and the (sometimes imperfect) final welds are applied to this beam pipe where the limited aperture is already important. We have addressed several persistent loss locations with alignment, re-welding, and other aperture improvement efforts. Such locations include RR315, RR419, RR421, RR425, and RR509. The RGD magnets have a nominal gap of 50.8 mm (2") at the center and a design beam pipe aperture of 44 mm (probably more like 40 mm actual). See Beams-doc-1382[1] for studies of activation when MI has reduced aperture.

We consider here replacing one gradient magnet pair with a pair of standard Recycler quadrupoles and a pair of newly designed dipoles. By specification, the 20" Recycler quadrupoles can provide the same focusing as an RGD. Using a 3" aperture circular pipe which fits through the Recycler quadrupoles may avoid vertical aperture limitations in any selected regular cell. For this note, we assume that focusing will be provided by a re-tuning of existing 20" quadrupoles as needed for the lattice design.

To provide the bending obtained by the RGD magnets one can explore options for aperture and magnet strength. If the dipole is far enough from the β_{MAX}, it may be sufficient to use the standard Main Injector or Recycler beam pipe and a 2” gap. To achieve the bend a shorter and stronger dipole can be specified or one can extend the bending into regions further from the β_{MAX} with a dipole strength typical of 2-brick-high magnet designs. A dipole design with a larger vertical aperture and a new beam pipe design can be considered if that better matches aperture and bend angle requirements.

Prior to detailed lattice and aperture considerations, we consider as an example a stronger 2” gap dipole which provides the bend of the RGD in order to reduce the required length to leave a place for the quadrupole. Using a spreadsheet for reluctance calculations, we have compared properties of the integral dipole field for various configurations. Simple reluctance calculations can provide an accurate magnet length requirement for different brick configurations. Let us consider replacing the ’two-brick-high’ RGD design (0.137 T) with a ’four-brick-high’ dipole. A detailed study is reported[2] for the PDD design used in the MI8 beamline. The PDD achieved higher fields (0.231 T) using side bricks and other tricks but that is not necessary here. The higher strength of a four brick design shows up as a reduced reluctance which gives a higher magnetic potential for the same source terms coming from the brick surface area.

To replace the bend from an RGD but reduce the length by the 24” required to leave a place for the standard quadrupole (with 20” pole length), either of two four-brick-high configurations could provide enough higher field to provide the required bending length reduction. Increasing the brick packing factor slightly would allow use of the 6” wide pole tip of the PDD or RGF. An 8” pole width would require a less dense brick packing factor. We assume in the spreadsheet calculation that we need 11% of the brick area to be covered with temperature compensator. It may be that an 8” wide pole will create a sufficient field quality to make this a very simple magnet with flat or nearly flat poles.

In addition to the bending and focusing components, the RGD has a significant sextupole. We can again add that to the body of the dipole or to an end shim (we got much of the RGD sextupole with end shims). We may be able to asymmetrically tune the quadrupole to provide sufficient sextupole.

My last consideration for this concerns the path length. If we move the bend center out, there will be a shorter path for the central orbit. I have not calculated that effect. If we need to do something different, adding a 3” aperture magnet between the 20” quadrupoles could be used to match the required path length. Perhaps this effect is small and can be ignored.

We have several half cells in the RR400 - RR500 region where loss remains significant. Perhaps we should consider replacing magnets in a few of these regions.

3 An Improved Recycler Horizontal Aperture at LAM232

At the Lambertsons, since the beam is extracted and injected horizontally, the circulating and transferred beam orbits must both fit in the horizontal aperture of the beam pipe. In Table 1 we indicate the magnitude of the circulating beam offset with the desired position[1] at the relevant horizontal BPM which is used for orbit smoothing. We also show the design width (95%) for a 15 pi-mm-mr injected emittance. These offsets and widths only characterize the magnitude of the issues. Details of the beam displacement and size as it changes along the orbit are needed to examine the aperture requirements. The transfer points are away from the β_{MAX}: LAM102 downstream of a vertically focusing half cell and LAM402 and LAM522 downstream of a horizontally focusing half cell. These cells use quadrupoles for focusing. Upstream of LAM232, we have a pair of SGF

[1] After exploring losses and transmission associated with each BPM, a desired position for that BPM is determined and that position used for the orbit smoothing program.

Table 1: Device List at Recycler Transfer Points: LAM = Lambertson, Q = quadrupole, H = horizontal trim, HP = Horizontal BPM, G = gradient magnet

102	232	402	522
Injection from Booster	Extraction to Main Injector	Abort	Extraction to Muon Campus
Q101B	HP232	HP402	HP522
LAM102	G232A	H402	Q522A
Q102A	G232B	Q402B	Q522B
H102	H232	LAM402	H522
HP102	LAM232	Q403A	LAM522
Q102B	G301A	Q403B	Q523A
Desired Position at Horizontal BPM (mm)			
-24	-21	-20	-27
95% Horizontal beam full width at upstream and downstream end of LAM (15 pi-mm-mr emittance) (mm)			
12.828,11.168	12.616,15.634	12.234,16.168	13.93,15.57

gradient magnets (horizontally focusing cell). Both the gradient and quad locations use the standard Recycler elliptical beam pipe with a nominal horizontal half aperture of 48 mm from the center.

The total horizontal aperture of the beam tube can accommodate both the circulating and the transferred beam if the circulating beam is not constrained to the geometric center of the magnet, though a little extra margin would be welcome. The issue is maintaining sufficient field quality for the circulating beam off-axis.

Two effects must be considered when displacing the closed orbit in a quadrupole, correcting the closed orbit for the dipole component of the field at the new location and accommodating any changes to the optics from the deterioration of the field shape from linear (constant gradient) at the offset location. Optics effects include a change in the gradient strength and additional higher harmonics. The orbit correction needs to be assessed. A quick look at the design fields for the 20" quads suggests that the gradient is down by 1.4% when offset by 47 mm (1.865") on the horizontal axis. When orbits are displaced by this much, the impact on the beam by one quad is perhaps acceptable. We should consider using a wider beam pipe such as a Main Injector elliptical pipe or with some exotic shape, allowing the transferred beam to travel through even less-desirable field, but this needs evaluation.

Similarly in the gradient magnets, we must assess the effect of offsetting circulating beam on the closed orbit and optics. A quick look at the SGF gradient uniformity shows that on the median plane at -50 mm (-1.972") we have a gradient increase of 4.3%, while at 51.5 mm (2.027") we have a decrease of 4%. This suggests that we are at the edge of the good field region and we may be degrading the circulating beam if we offset the closed orbit through these magnets by a 25 mm (1") offset. We can consider using a wider beam pipe with some exotic shape but this field quality issue suggests that we need to review more options. See Beams-doc-4880[3] for field maps.

To address the field quality, we propose that a pair of 20" quads provide the focusing for the 232 half cell and a pair of stronger dipoles be built to provide the bending. For these dipoles, the Recycler standard 25.4 mm (2") vertical gap is sufficient. We can fit a Main Injector elliptical pipe through the 20" quad or consider a special beam pipe with a larger horizontal aperture to open the aperture for the transferred beam while keeping the circulating beam closer to the magnetic center.

For the bend of the shorter SGF magnet it is hard to save 24" for inserting a quadrupole. If we reduce the pole length from 122" to 98", we can barely manage with a 6" wide pole and four-brick-high driving term. The spreadsheet suggests that a reasonable brick fraction on the top of an 8" wide pole will provide adequate strength. The SGF design does not include a sextupole component, so that is not an issue.

4 Conclusion

The aperture limitation of the regular cell vertical high beta points could be removed with a new design gradient magnet or a combination of reused quads and new dipoles. The choice requires further study and will depend in part on the number of magnets to be replaced. At three Lambertsons, it appears that small changes in quad alignment and beam tube geometry could remove the horizontal aperture limitations. We may wish to replace the permanent magnet Lambertson at 402. At LAM232 a relatively simple set of replacement magnets, one old (re-tuned) quad and one new dipole per SGF, can remove the horizontal aperture limitation there.The 2012-2013 Recycler upgrade left us with many quadrupoles which can be re-tuned for this use. We should mention that the existing Recycler gradient magnets are 9" high which requires 4.5" of the 12" between the beam height and the ceiling. A four-brick-high design would place the top of the magnet at 6.5" which still leaves 5.5" to the ceiling.

We are introducing a simple option: Gradient-Gradient ⇒ dipole-quad-quad-dipole. One will also review alternatives in which Gradient-Gradient ⇒ dipole-quad-dipole or dipole-quad-dipole-quad-dipole for the problem areas we have identified. We recall that larger aperture quadrupoles exist which were developed and installed for an initial cooling insert of the Recycler. We consider using the same strontium ferrite to drive new magnets but if design problems appear one can use stronger permanent magnet materials.

Given these building blocks, the next step for exploring these concepts should be a more detailed look at the lattice in conjunction with simple considerations of possible magnet properties. With a better understanding of the requirements, magnet designs can then be refined.

5 Acknowledgments

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References

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